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# Improving quality of strawberry by novel essential oil nanoemulsions of *Echinophora platyloba* combined with *Aloe vera* gel and gum arabic

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**Strawberry fruits are highly perishable and have a limited shelf life. Therefore, effective methods such as essential oils (EOs) and edible coatings are required to mitigate spoilage and maintain fruit quality during storage. In the current study, *Echinophora platyloba* EO was extracted and subsequently formulated into a nanoemulsion. The strawberries were then coated using an immersion method with the prepared nanoemulsions, gum Arabic (GA), and Aloe vera gel (AV). The coating treatments included: distilled water control, 5% GA, 20% AV, 0.5% *E. platyloba* essential oil, 5% GA + 0.5% *E. platyloba* nanoemulsion essential oil, and 20% AV + 0.5% *E. platyloba* nanoemulsion EO. The quality of strawberries was assessed over a storage period of 3, 6, 9, 12, and 15 days. The results revealed that the EO nanoemulsion in combination with GA and AV gel coatings provided superior preservation compared to the control and single-component treatments (pure EO, GA, or AV gel). Coatings with 5% GA + 0.5% EO nanoemulsion and 20% AV + 0.5% EO nanoemulsion demonstrated the highest firmness while achieving the lowest weight loss, titratable acidity (TA), total soluble solids (TSS), TSS/TA ratio, decay percentage, and tissue browning at the end of the storage period. Notably, the decay index in the 20% AV + 0.5% EO nanoemulsion treatment was 17% lower than the 5% GA + 0.5% EO nanoemulsion treatment and 75% lower than other treatments after the experiment. These coatings are recommended due to their eco-friendly, biodegradable nature and cost-effectiveness, making them a promising solution for enhancing the shelf life and quality of strawberries.**

**Keywords** Nanotechnology, Edible coating, Storage, Quality, Shelf life

The strawberry (*Fragaria ananassa*) belongs to the Rosaceae family and is widely recognized as one of the most important and delicious small fruits globally[1]. Due to their high popularity, strawberries are consumed both fresh and in various processed forms, including juice, pies, jam, ice cream, chocolates, and milkshakes. They are highly beneficial to human health, being rich in vitamin C and manganese, and also providing significant amounts of folate and potassium. Strawberries are among the richest sources of bioactive compounds with antioxidant properties, which help protect against harmful free radicals[2,3]. Despite an annual global production of over 8.1 million tons in the past 5 years[4], postharvest losses of strawberries are estimated to reach up to 40%[1].

Strawberry is classified as a non-climacteric fruit, meaning that it does not continue to ripen after harvest. Hence, these fruits must be harvested at full ripeness to ensure the optimal quality in terms of color and flavor. However, the fruit has very short postharvest longevity, often lasting less than five days. Several studies have revealed that significant postharvest losses are related to high cell respiration rate, fungal decay, mechanical damage and water loss[2,5]. Additionally, the delicate nature of fruit skin makes it highly susceptible to surface crushing during the during harvesting and transportation stages. After picking, the strawberry exhibits high respiratory activity and increased sensitivity to mechanical damage, as well as infection by plant pathogens including bacteria, fungi, and viruses[3,6].

Numerous procedures, such as cooling, modified atmosphere packaging, active packaging, edible film coating, UV radiations, and fruit sanitization, are carried out to lower the respiration rate and water loss, maintain fruit firmness, and control microbial spread. These are all objectives of postharvest operations to extend the fruit's shelf life[3,5–7]. In recent years, there has been a surge in interest in edible film coating to enhance

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fruit longevity and impede tissue damage[5,7]. Renewable edible coatings function by providing a physical barrier around fruits, protecting them moisture loss, gasses, and microorganisms that could compromise their quality. In recent decades, edible coatings such as cellulose, starch, chitosan, gum Arabic, *Aloe vera* gel, and essential oils have gained prominence in replacing synthetic counterparts in the postharvest of fruits such as strawberries[5,7–9].

Gum Arabic (GA) is one of the most important edible coatings. GA, as a bio-polysaccharide, is primarily obtained from the *Acacia senegal* tree. It is a bio-composite polysaccharide, consisting of protein, arabinose, galactose, glucuronic acid, and rhamnose[10]. GA characterized by its high solubility and low viscosity. Notably, it has been commercially used as an edible coating on fruits such as papaya, Mexican lime[11], strawberry[12], and grape[9]. Tahir et al. reported that 15% of GA-coating can effectively enhance the quality of strawberry fruits during cold storage without any negative effects[12].

In recent years, the use of *Aloe vera* gel has gained much attention due to its environmental friendliness and strong antimicrobial properties, making it a promising coating agent. The positive effects of *Aloe vera* gel as a coating have been demonstrated in various fruits such as sweet cherries, table grapes, nectarines, and papaya. Furthermore, it has been shown to reduce the water loss, fruit softening, respiration rates, oxidative browning and microorganism proliferation. Ultimately, enhancing the fruit quality during the postharvest stage[8,13]. Recently Tabing et al. noted that both *aloe vera* coating and packaging materials significantly influenced the postharvest life of strawberry fruits. Among all tested treatments, the combination of 100% *Aloe vera* gel and polyethylene packaging was found to be the most effective[14].

Nowadays, public interest increasingly shifted toward the use of plant derived compounds as natural food preservatives, creating opportunities for the production of safe foods with a natural or green image. Moreover, the increasing consumer preference for natural products over synthetic ones and the growing demand for higher-quality foods are key factors driving food industries to include healthy EOs in their products[15]. *Echinophora platyloba* a member of the Apiaceae family, is native to Iran and primarily distributed in the western and North-Western of the country[16]. Because of its desirable aromatic and antimicrobial properties, this species has traditionally been added as a spice to cheeses, tomato paste, and pickled cucumber[17,18]. Sharifian and Darvishzadeh reported that (Z)-β-ocimene (33.06%), p-cymene (10.98%), and Limonene (5.77%) as the major constituents of *Echinophora platiloba* DC from Zagros foothills, Iran[19]. However, the application of essential oils (EOs) is limited due to their low water solubility, high vapor pressure, and physical and chemical instability[20].

On the other hand, nanotechnology has facilitated a significant progress across various scientific fields and innovations[21]. In recent years, nanotechnology has emerged as a transformative toll in agriculture, offering diverse applications in crop production, processing, storage, packaging, and transportation[5]. Although, EOs have been widely studied as natural antimicrobial components in recent years. The employment of EOs is often limited owing to their poor water solubility, volatility, physical, and chemical instability. In addition, EOs can affect sensory properties of fruits because of their strong odor and taste[21,22]. Nanoemulsions are designed for nanosized delivery systems designed for lipophilic compounds such as antimicrobials, vitamins, and flavors. These nanoemulsions are highly stable against flocculation and coalescence, making them excellent candidates for food industries[23]. Thus, incorporating EO nanoemulsions into edible coatings can help preserve the quality and freshness of fruits and vegetables[21]. Basically, nanoemulsions are produced using one of two methods high-energy and low-energy emulsification systems. High energy is operated with mechanical energy and low energy is operated with chemical energy[24]. However, no earlier research has explored the impact of essential oil nanoemulsion in combination with GA and AV on postharvest quality in strawberries. Therefore, the present study aimed to investigate the effect of an EO nanoemulsion derived from *E. platyloba*, along with GA and AV gel coating and subsequent packaging, on the postharvest life of strawberries during storage at 4 °C for 15 days.

## Materials and methods

### Plant materials and treatments

The research was conducted on strawberries (*Fragaria × ananassa* cv. Albion), which were purchased from a greenhouse in Iran in 2024 (Fig. 1A). The harvest date was determined based on the fruit surface coloring,


**Fig. 1**. Strawberries cv. Albion before coating (**A**), immersion in coatings (**B**) and packaging after coating (**C**).

aligning with a commercial maturity stage (>80% red surface color). The strawberries were selected for uniform in shape, size, and color ensuring they were free from pests and mechanical damage. Then, they were immediately transferred to the postharvest physiology laboratory of the Department of Horticulture, University of Arak for treatment application. Fruits were randomly divided into six groups of 30 for coating treatments, with three replicates per treatment. Each replicate contained 10 fruits. The coating treatments included: (1) control: immersing fruits in distilled water for 3 min; (2) immersion in 5% GA for 3 min (Fig. 1B); (3) immersion in 20% AV for 3 min; (4) immersion in 0.5% EP essential oil for 3 min; (5) immersion in 5% GA + 0.5% EP nanoemulsion essential oil for 3 min and (6) immersion in 20% AV + 0.5% EP nanoemulsion essential oil for 3 min (Fig. 1B). All established sets contained 4 replicates (4 polyethylene terephthalate containers). These treatments were selected based on preliminary experiments in the laboratory (Fig. 1C). After air-drying, the fruits were packaged in polyethylene terephthalate (PET) boxes (dimensions of 13 × 10 × 5 cm), covered with their lids, stored in storage at 4 ± 0.5 °C and 80% relative humidity in the dark chamber[7]. Six fruits from each replicate were sampled and analyzed on days 3, 6, 9, 12, and 15.

## Preparation of *Echinophora platyloba* essential oil

Plant material was collected between June and July 2024 from Arak, Markazi Province, Iran. The aerial part was shade-dried, avoiding dried away from direct sunlight, and ground into fine powder (approximately 0.4 mm particle size) using a blender. The EOs were extracted via hydrodistillation for 8 h using a Clevenger-type apparatus (60 g of sample in 500 mL of distilled water), as recommended by British Pharmacopeia. The extracted oils were used without further purification[25].

## Preparation of nanoemulsion essential oil of *Echinophora platyloba*

Nanoemulsions of *E. platyloba* essential oil were prepared following the method described by Moradi and Barati with modifications. Tween 80 (6% v/v) and Span 60 (1% v/v) were dissolved in double-distilled water at room temperature and vortexed for 15 min. Essential oil (2% v/v) was gradually added to the mixture, which was stirred with a magnetic stirrer (Fine TECH, SDS-41; South Korea) for 25 min[23].

## Characterization of essential oil nanoemulsion

*Particle size measurements*

Particle size was determined using dynamic light scattering (DLS) analysis (MAL1008078, Malvern, UK). This technique measures the particle size based on intensity-time fluctuations of a laser beam (633 nm) scattered from a sample. The mean particle size, or Z-Average size, obtained through cumulants analysis, was reported as the intensity-weighted mean diameter. To prevent multiple scattering effects and ensure measurement accuracy, samples were diluted with distilled water at a 1:10 ratio before analysis. Measurements were conducted in triplicates to ensure reproducibility and reliability[21,23].

*Turbidity*

Turbidity was assessed visually one-month post-production, with measurements performed at least three times for each sample[23].

## Preparation of gum arabic and *Aloe vera* gel

AV leaves were purchased from a local nursery in Iran. To prepare its gel, leaves were peeled using a stainless steel knife, and the gel was extracted. The mixture was subsequently combined and homogenized using a blender, followed by filtration to remove any impurities and debris. A solution containing 20% AV compound was prepared by mixing AV (20 mL) with 80 mL of distilled water. This combination was selected because films made from these materials exhibited superior barrier and mechanical strength in our previous study[26].

## Evaluated parameters during the storage period

*Weight loss percentage*

Weight loss was determined by weighing the strawberries before the experiment (initial weight) and after storage on days 3, 6, 9, 12, and 15. The percentage of weight loss was calculated according to Eq. (1)[5,9]:

$$(\text{Weight before storage} \ - \ \text{Weight on sampling day}) / \text{Weight before storage} \ \times 100. \qquad (1)$$

*Total soluble solid (TSS)*

The total soluble solids content (TSS) of the berries was determined using a handled refractometer (Atago, PAL-1. Kyoto, Japan) in % (Brix)[9].

*Titratable acidity (TA) and TSS/TA ratio*

Total acidity (TA) was assessed through titration with 0.1 N sodium hydroxide until a pH of 8.1 was reached. This procedure involved the use of 1 mL of diluted juice combined with 25 mL of distilled water. The findings were reported as a percentage of tartaric acid. TA expressed as a percentage. TSS to TA ratio was calculated by dividing TSS by TA[5,20].

*Fruit firmness*

Fruit firmness was determined using a handheld hardness analyzer (FT011, Facchini srl, Alfonsine (Ra), Italy) with a 2 mm probe. The results were expressed in newtons (N) cm$^{-2}$[5].

*Decay percentage*
The percentage of decayed fruits due to storage rot was recorded. The decay percentage was determined based on the initial quantity of fruit in each sample and expressed as a percentage. The scoring method was used to evaluate the decay rate of fruits. Therefore, the fruits were categorized into five groups based on the degree of decay and scored as: 1 = fruits without decay; 2 = fruits with decay covering less than 25% of the surface; 3 = fruits with decay covering between 25 and 50% of the surface; 4 = fruits with decay covering between 50 and 75% of the surface, and 5 = fruits with decay covering between 75 and 100% of the surface[27].

## Browning index
Hunter a, b and L parameters of strawberry purees were determined with Adobe Photoshop CS6 3D (Version13.1.2 Extended 2016) in the reflection mode. The instrument was calibrated with a white ceramic plate (L = 96.55, a = − 0.35, b = − 0.16). Browning index (BI) was calculated according to the following Eqs. (2) and (3):

$$\mathrm{BI} = [100\ (\mathrm{x}\ 2\ 0.31)]\ /0.172, \tag{2}$$

where

$$\mathrm{x} = (\mathrm{a}\ 1\ 1.75\mathrm{L})\ /\ (5.645\mathrm{L} + \mathrm{a}\ 2\ 3.012\mathrm{b})\,. \tag{3}$$

The browning index (BI) indicates the intensity of brown coloration and is a significant parameter in processes involving either enzymatic or nonenzymatic browning[28].

## Experimental design and data analysis
The present study was carried out as a factorial experiment based on a completely randomized design (CRD) with two factors. The first factor was the storage period (3, 6, 9, 12, and 15 days) and the second was the coating treatments. Data were analyzed using a General Linear Model (GLM) procedure in SAS software (ver. 9.1). Significant differences were assessed using Duncan's multiple range test ($P \leq 0.05$). Each treatment group consisted of three replications.

## Results and discussion
### Physiochemical properties
Images of nanoemulsion prepared with 2% *E. platyloba* EOs are shown in Fig. 2. Accordingly, emulsions prepared without surfactants (Tween 80 and Span 60) are turbid, while those prepared with both surfactants are transparent. This difference can be attributed to smaller particle diameters, leading to the more transparent solutions. Similarly, Moradi and Barati showed that the Tween 80 and SDS surfactants treatments enhanced the transparency of Shirazi thyme nanoemulsion's Eos[23].

**Fig. 2**. Visual appearance of *Echinophora platyloba* essential oil nanoemulsions; Left: Nanoemulsion formulated with 6 v/v% Tween 80, 1 v/v% Span, and 2 v/v% essential oil. Right: Nanoemulsion prepared without the aforementioned surfactants. Both images depict the appearance of the nanoemulsions two months after production.

The results of DLS analysis exhibited that the mean droplet sizes of nanoemulsion prepared with 6 v/v% Tween 80 and 1 v/v% Span was approximately about 45 nm. Additionally, the formulated essential oil nanoemulsion remained physically stable over the 4 months of storage at room temperature which makes it a promising candidate for practical applications. Similar results have been reported by some authors[21,23]

## Weight loss percentage

According to ANOVA, significant interactions were observed between storage times and coating treatments for all measured parameters except for titratable acidity. The weight loss of strawberry samples during the preservation period is shown in Fig. 3. A progressive increase in weight loss was observed for all treatments throughout storage, attributable to the continuous loss of water from the strawberries to the surrounding environment. All coating solutions significantly mitigated weight loss compared to the control. However, the most effective treatment in minimizing weight loss was the combination of 0.5% essential oil nanoemulsion with 5% GA and 20% AV. At the end of storage, the control fruits exhibited a 4.57% weight loss, while fruits treated with the aforementioned combination demonstrated significantly lower weight loss, at 2.57% and 2.46%, respectively. The main reasons for weight loss in fruits are transpiration and respiration processes[8]. According to Shiina, the commercial value of strawberries would be compromised if their water content were reduced by 5% or more. Edible coatings form a transparent layer over the fruit, effectively sealing minor injuries[29]. As a result, weight loss is reduced for coated fruits throughout the storage duration. The coatings act as semi-permeable barriers, reducing transpiration and controlling $O_2$ and $CO_2$ exchange, thereby slowing respiration[5]. All the fruits in the edible coating treatments displayed significantly smaller weight loss as compared to control fruits. Reducing in weight loss of strawberries with the application of AV, GA and EOs nanoemulsion has been reported for strawberries[5,6,14], cherries[8], and table grape[9], which is consistent with the results of the present work. Agreeing with our findings, Javanmardi et al. showed that Nano-EM of both *Thymus vulgaris* and *Mentha longifolia* EOs reduced weight loss and induced greater firmness, vitamin C, total flavonoid and antioxidant activity in strawberry during storage[22].

## Total soluble solid

Similar to weight loss percentage, significant interactions were observed between storage period and coating treatments for TSS. Considerable increases in the TSS were observed for all treatments during the storage period. Excluding 0.5% EO on day 9, the TSS of strawberries was reduced by all coating solutions compared to the control (Fig. 4). From the 9th day to the end of storage, fruits coated with 0.5% essential oil nanoemulsion in combination with 5% GA and 20% AV exhibited the lowest TSS level (6.75 Brix) compared to the control (8.6 Brix). The TSS content in strawberries commonly used to evaluate ripeness, as fully matured strawberries contain the highest levels of soluble solid[6]. The higher TSS values in the four treatments without nanoemulsions were attributed to the continuous conversion of starch into soluble sugars as the storage period progressed. While, 0.5% essential oil nanoemulsion in combination with 5% GA and 20% AV films exhibited better inhibition of strawberry respiration and inhibition of metabolic enzyme activity compared to other treatments. As a result, the increase in soluble solids in strawberries coated with 0.5% essential oil nanoemulsion, 5% GA, and 20%

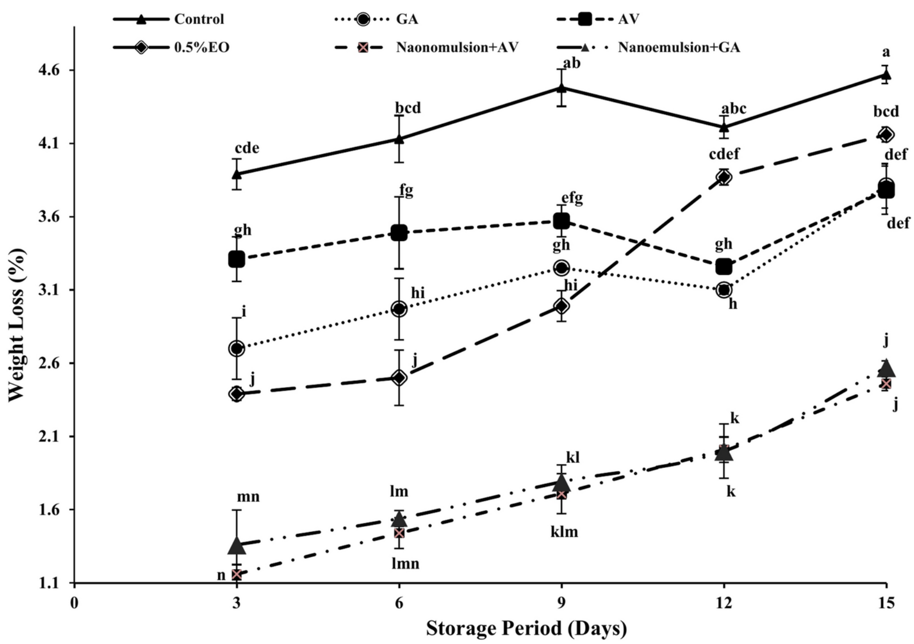


**Fig. 3**. Interaction of storage period and coating treatments on the weight loss percentage of Albion strawberries during the storage. Mean values followed by the similar letters are not significantly different from each other at $P \leq 0.05$. Each bar corresponds to the mean ± SE (n = 6).

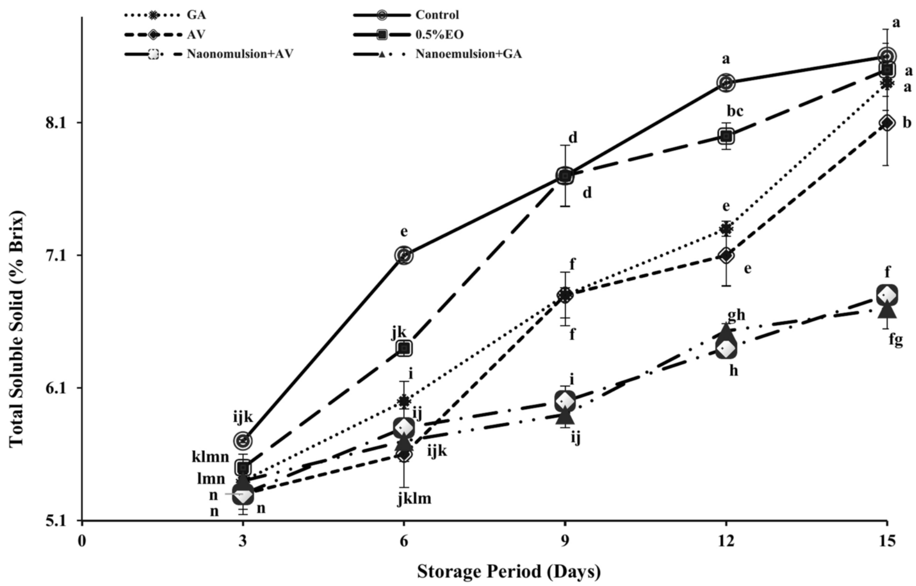


**Fig. 4**. Interaction of storage time and coating treatments on the TSS (Brix) of Albion strawberries during the storage. Mean values followed by the similar letters are not significantly different from each other at $P \le 0.05$. Each bar corresponds to the mean ± SE (n = 6).

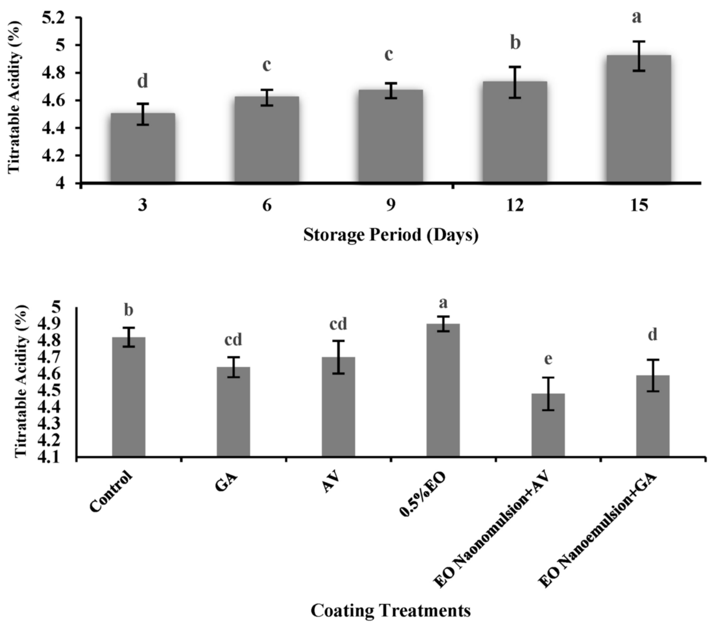


**Fig. 5**. Left; Effect of storage period and Right; coating treatments (right) on the TA content of Albion strawberries during the storage. Mean values followed by the similar letters are not significantly different from each other at P ≤ 0.05. Each bar corresponds to the mean ± SE (n = 6).

AV was slower. Zhang et al. reported that PLA/Ag 5% and PLA/Ag 10% films exhibited lower levels of TSS, supporting our findings[6]. Additionally, Marpudi et al. reported a lower TSS content in papaya fruits coated with AV gel during storage compared to uncoated fruits[30].

## Titratable acidity and TSS/TA ratio

Although, the effect of storage time and coating treatments was significant on TA, their interaction did not show a significant effect. TA exhibited an ascending trend during the storage period (Fig. 5). The reduction of organic acids during storage may be associated with metabolic alterations or the utilization of these acids for respiration, as observed in strawberries[5]. The lowest TA level was observed in essential oil nanoemulsion in combination with 20% AV (4.48%). While the highest level was found in 0.5% EO (4.90%), the control showed a higher level

(4.82%) than EO nanoemusion compounds (Fig. 6). The TA level in strawberries is a critical determinant of their taste quality. As the respiratory metabolism of the fruit increases, there is a concomitant decrease in acid content[6]. This study's findings demonstrate that nanoemulsion coatings effectively inhibit strawberry respiration, thereby reducing the consumption of acids during physiological metabolic activities. Consequently, the application of nanoemulsion coatings mitigates the decline in TA, contributing to an extension of the strawberries' shelf life. The TSS/TA ratio followed the same trend as TSS (Fig. 6). The results indicated that the TSS/TA ratio of strawberries increased during the storage period. The TSS/TA ratio was reduced by all coating essential oil nanoemulsions compared to the control. The TSS/TA ratio is a key factor in determining the acceptability of fruits, such as strawberries, by consumers. Similar to the findings of this study, an increase in TSS, TSS/TA, and a decrease in TA during the storage period have been reported for strawberries[20,31], cherry[8] and mangos[32]. These changes are related to the increase in respiration rate, consumption of organic acids, water loss, and the catabolism of polysaccharides into simple sugars[5,6,8]. Moreover, the positive effects of AV, GA, and essential oil nanoemulsion on TSS, TA, and TSS/TA ratio have been reported for strawberries[20,31], and duke cherry[8], which is consistent with our findings.

## Firmness

The firmness of fruit is a crucial factor in assessing the postharvest quality of strawberries. Significant interactions were observed between the storage period and coating treatments regarding fruit tissue firmness. Accordingly, this parameter decreased over the storage period for all treatments, with a slower decline observed in all coated treatments compared to the control. The lowest firmness was observed in control while the highest value was found in EO nanoemulsions in combination with 5% GA and 20% AV (Figs. 7, 8). These results align with previous studies, which report a decrease in the firmness of strawberries during storage[5–7,20]. Earlier research indicated that the strawberry's tissues soften over time of the metabolic alterations and, moisture loss associated with the enzymatic activity, ultimately leading to decreased in the fruit firmness[6]. Strawberry's softening process can be explained by the alterations in the cell wall, including the loss of hemicellulose and galactose, and the dissolution of pectin, all resulting from the increased activity of cell wall hydrolyzing enzymes[5,20]. Confirming our findings, Javanmardi et al. reported that coated strawberries with 0.5% nanoemulsion of thyme combined with 0.5% carboxymethyl cellulose retained higher firmness compared to uncoated fruits[20]. The positive effects of coating treatment, particularly EOs nanoemulsions compounds in reducing fruit softening might be attributed to their role in decreasing the activity of enzymes such as β-galactosidase, polygalacturonase, and pectin methylesterase, as well as reducing respiration rates, thus slowing the ripening process[5,6,8,20]. These results suggest that *E. platyloba* EO released from the nanoemulsion maintained the integrity of the fruit's cell wall and reduced moisture loss, consistent with similar previous studies[7]. Ruskova et al. reported that softening and loss of firmness were significantly reduced in strawberries coated with a nanoemulsion combined with GA and AV[7]. Furthermore, Javanmardi et al. showed that Nano-EM of both *Thymus vulgaris* and *Mentha longifolia* EOs reduced microbial load, decay index, weight loss and induced greater firmness, vitamin C, total flavonoid and antioxidant activity in strawberry during storage[22].

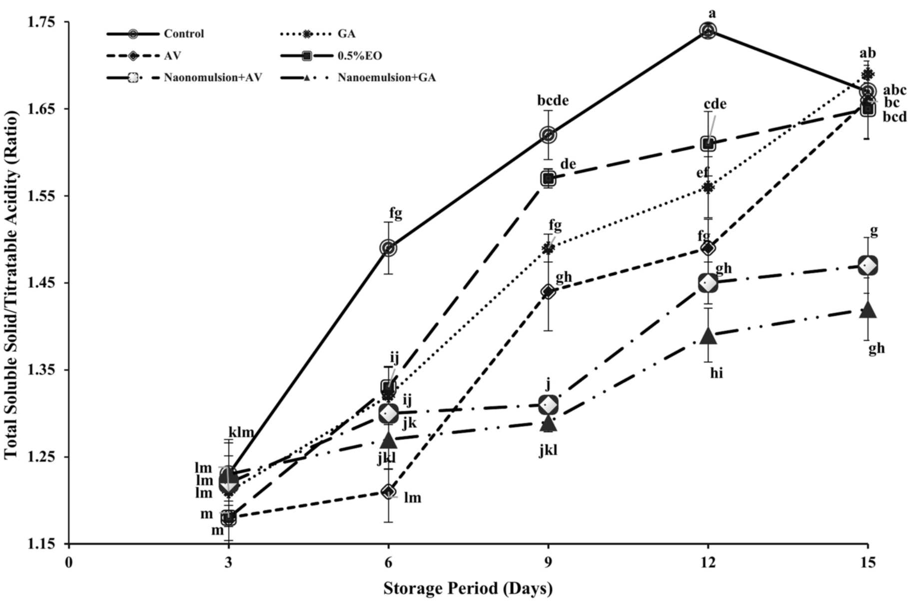


**Fig. 6**. Interaction effect of storage time and coating treatments on the TSS/TA ratio of Albion strawberries during the storage. Mean values followed by the similar letters are not significantly different from each other at $P \le 0.05$. Each bar corresponds to the mean ± SE (n = 6).

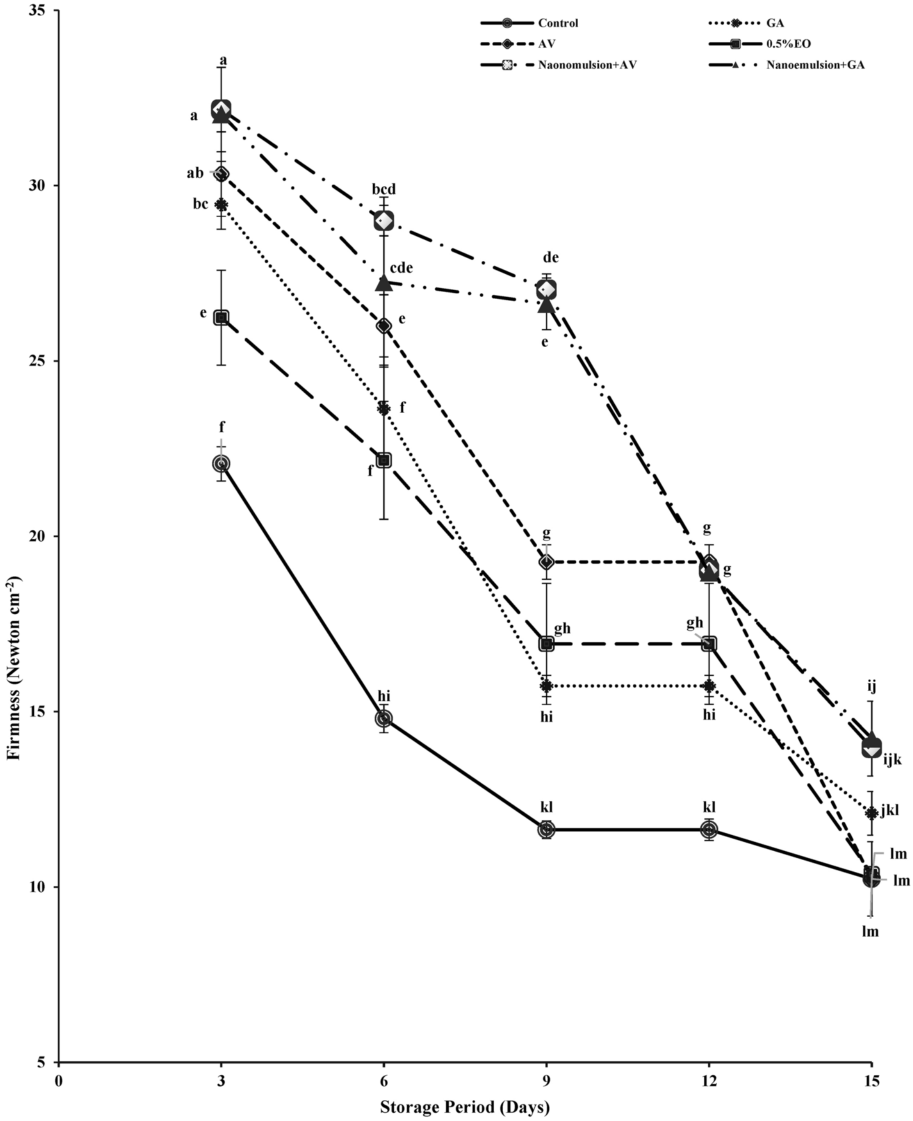


**Fig. 7**. Interaction effect of storage time and coating treatments on the firmness of Albion strawberries during the storage. Mean values followed by the similar letters are not significantly different from each other at $P \leq 0.05$. Each bar corresponds to the mean ± SE (n = 6).


**Fig. 8**. Visual appearance of Albion strawberries after 12 days of storage at 5 °C: (**A**) uncoated control, (**B**) coated with 5% gum Arabic (GA), (**C**) coated with 20% *Aloe vera* (AV), (**D**) coated with 0.5% essential oil nanoemulsion, (**E**) coated with a combination of 20% AV and 0.5% essential oil nanoemulsion, and (**F**) coated with a combination of 5% GA and 0.5% essential oil nanoemulsion.

## Decay percentage

The storage period, coating treatments and their interactions significantly affected the decay percentage of strawberry fruits. As shown in Fig. 9, no visible decay was observed in both the control and coated strawberries after 3 days of storage. However, decay symptoms appeared in both control and coated fruits on day 6. Though there were no significant differences, control exhibited the highest decay on day 9. At the end of storage, the control exhibited the maximum spoilage percentage (100%), while all the fruits rotted. Conversely, EO nanoemulsion coatings especially when combined with 20% AV effectively controlled the decay with only 20% spoilage observed at the end of storage. The decay percentage of fruits in this superior treatment was 17% lower than nanoemulsion + 5% GA, and 75% lower than other treatments at the end of the experiment (Fig. 8). Strawberries are highly susceptible to rapid spoilage due to microbial contamination, mechanical damage, or softening in texture[7]. As shown in Fig. 9, the application of 5% GA, 20% AV and 0.5% essential oil alone did not effectively control the spoilage contamination. However, the positive effect of GA and AV coatings in reducing decay has been described in strawberry fruits[14,31] and other fruits[8,9]. There is, however, no prior report on the simultaneous application of these compounds with EO nanoemulsions. The obtained results revealed that the application of GA and/or AV in combination with *E. platyloba* essential oil nanoemulsion was the most effective treatment for inhibiting decay in strawberry fruits.

In this research, the reduction of decay in strawberry fruits is can be attributed to EO nanoemulsion form *E. platyloba*. Previous studies have shown that ß-Cimen and p-Cimen are the main EO in this medicinal plant with confirmed antimicrobial and antioxidant properties[19,33]. EOs, which contains various chemical components, may destroy microorganisms through different mechanisms. The most important one is related to the hydrophobicity of the components, which enables them to penetrate cell and mitochondrial membranes, leading to cell dysfunction, increased permeability, and leakage of ions and other cellular contents[20,34]. Furthermore, due to the smaller size of nanoemulsions, they are more effective against infectious agents, making them an excellent candidate for use in the food industry and as coating treatments in the postharvest management of fruits such as strawberries[21,23]. Consisting with these results, Javanmardi et al. were studied the application of *Thymus vulgaris* and *Mentha longifolia* EOs and their nano-EM at 0.021, 0.1, 0.5 and 1% to control *B. cinerea* growth on the strawberry fruit surface. They indicated that Nano-EM of EOs had higher antifungal activity in the control of *B. cinerea* than EOs on fruit surface[22].

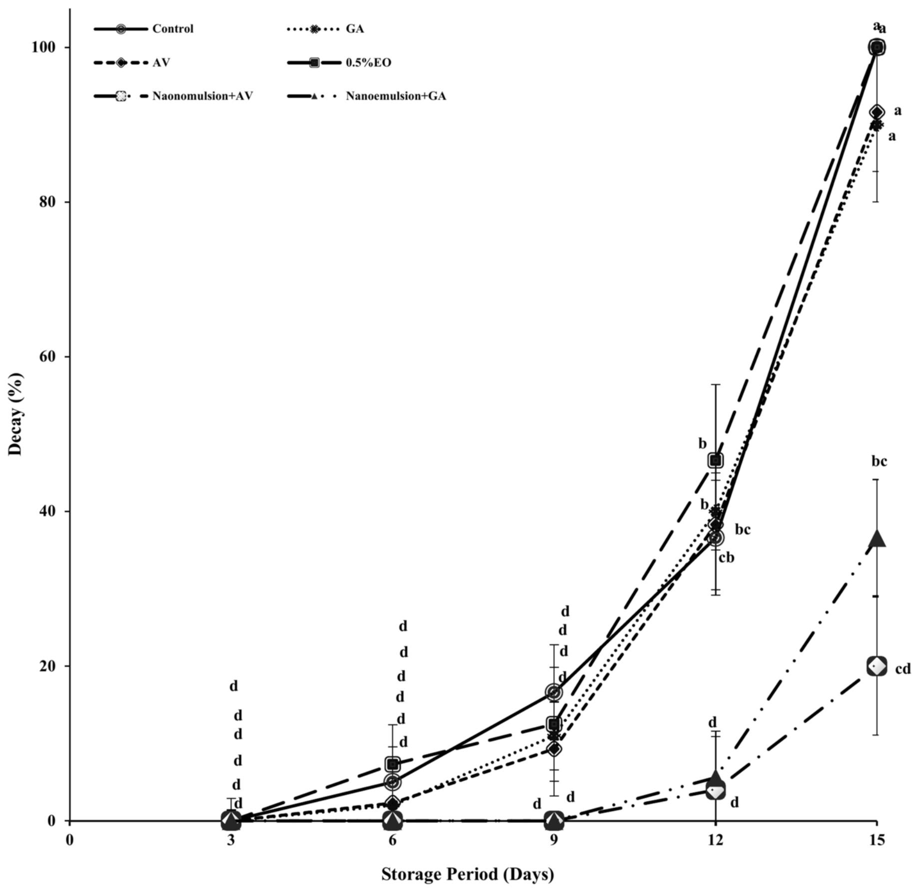


**Fig. 9**. Interaction effect of storage time and coating treatments on the decay percentage of Albion strawberries during the storage. Mean values followed by the similar letters are not significantly different from each other at $P \leq 0.05$. Each bar corresponds to the mean ± SE (n = 6).

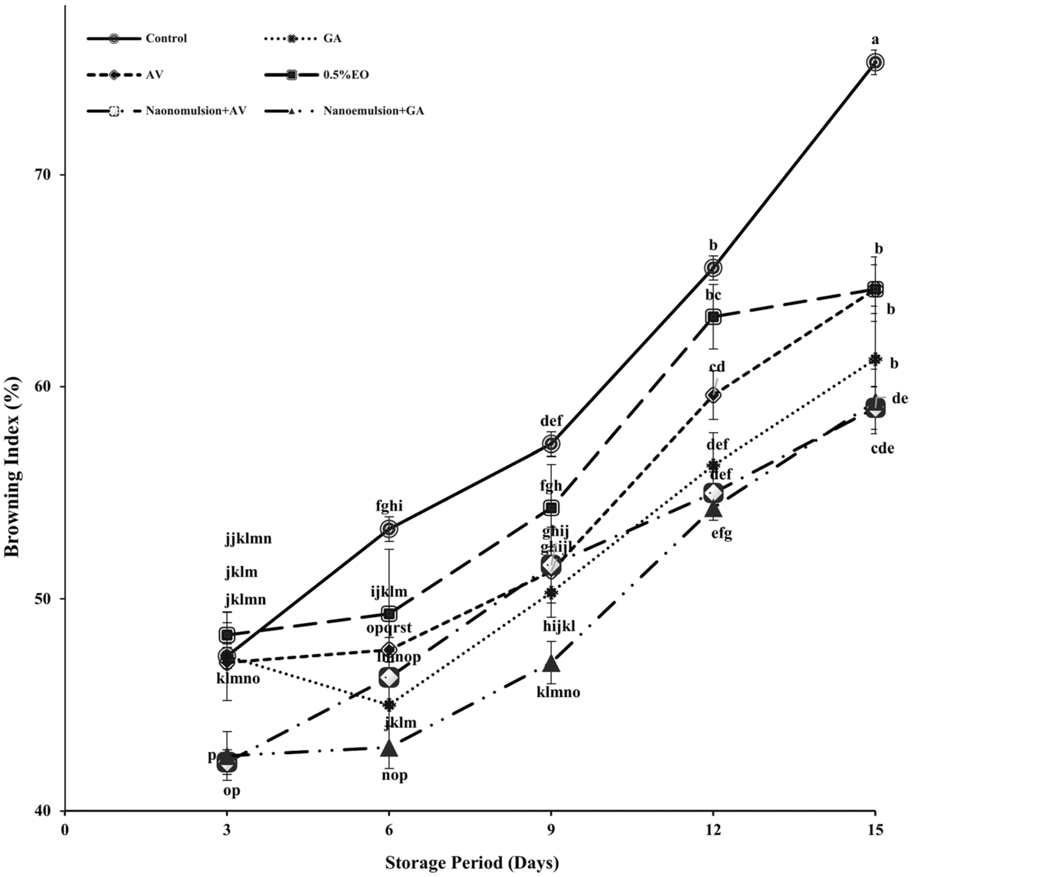


**Fig. 10**. Interaction effect of storage time and coating treatments on the browning index of Albion strawberries during the storage. Mean values followed by the similar letters are not significantly different from each other at $P \leq 0.05$. Each bar corresponds to the mean ± SE (n = 6).

## Browning index

Significant interactions were observed between the storage period and coating treatments for the browning index of strawberries. Browning increased in all treatments over the storage period, though the rate of increase was slower in fruits treated with EOs nanoemulsion combined with 5% GA compared to other treatments. The control exhibited the highest browning index, whereas the 0.5% EO nanoemulsion combined with 5% GA resulted in a significantly lower browning index than other treatments. However, no significant difference was observed between this treatment and the 0.5% essential oil nanoemulsion combined with 20% AV on days 12 and 15. During storage, discoloration primarily manifests on the surface of the strawberry, typically as darkening or spoilage, which substantially diminishes the fruit's nutritional value and sensory appeal[6]. The Browning index representing the intensity of brown color, serves as a critical parameter in evaluating processes involving enzymatic and non-enzymatic browning[34]. Besides, enzymatic browning is predominantly driven by the oxidation of polyphenolic compounds, catalyzed by endogenous polyphenol oxidase (PPO), presenting a significant postharvest challenge in strawberries[6]. Chief components of essential oils might be used against enzyme browning in fruit by delaying the amount at which oxygen is transferred between cells[35]. As well, the vapor of some essential oils can delay color change due to delayed ripening on the fruit surface, similar to findings by Owolabi et al.[36]. Herein, the application of EOs nanoemulsion coatings demonstrated superior efficacy in preserving the surface color of strawberries compared to other treatments (Fig. 10). Consistent with these findings, Ruskova et al. reported that active membrane packaging with oregano essential oil effectively retained the hue, thereby decelerating the ripening process[7]. Furthermore, Zhang et al. observed that the color difference value of fruits packaged in polyacetic acid (PLA) active films containing 5% nano-silver was lower than the initial value, highlighting the potential of such treatments in maintaining the visual and sensory qualities of fruits during storage[6]. Recently, Promwee and Matan reported that preharvest application of citrus oil nanoemulsion (0.006%) significantly reduces browning in postharvest chili, which is accordance of our results[37].

## Conclusion

This study established the effectiveness of a new technique for increasing shelf life and maintaining the postharvest quality of strawberry fruits during storage. Essential oil Nanoemulsions of *Echinophora platyloba* were formulated by low-energy emulsification systems and the physical stability of Nanoemulsions was appropriate for up to 120 days at room temperature. The application of essential oil nanoemulsion in combination with gum Arabic and *Aloe vera* as coatings had successfully extended shelf life to at least 15 days. Also, *Echinophora platyloba* nanoemulsion minimized weight loss and decay index, and maintained total soluble solids, texture firmness, skin color, titratable acidity and TSS to TA ratio. The prepared *Echinophora platyloba* based nanoemulsion is recommended due to its cost-effective method and serving to maintain quality during storage and transportation, and improve marketability of strawberry fruits.

## Data availability
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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## Author contributions

I.K.: Investigation, Data Duration, Methodology M.S.: Supervision, Validation, Original Draft preparation, Software M.V.: Supervision, Editing.

## Competing interests

The authors declare no competing interests.

## Additional information

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